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BLAST TRANSMISSION INTO CHAMBERS

by

George Chertock, Ph.D.

STRUCTURAL MECHANICS LABORATORY

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ABSTRACT

Equations are derived for the pressure rise in a terminal room or chamber due to the propagation through a duct system of a transient pressure from an external blast pressure wave. Numerical values for the peak pressure in the chamber are given in terms of the parameters of the blast pressure wave and the characteristics of the duct-chamber system. The calculation of the relevant characteristics of the duct-chamber system is described and illustrated in an appendix.

INTRODUCTION

A significant hazard from an air burst of a nuclear weapon arises from the possible penetration of the blast pressures into a structure. The propagation of relatively low air-blast pressures down a smokestack could severely damage a fire-box or boiler system. The penetration of blast pressures through a ventilation duct and into a protective shelter could do serious damage within the shelter, yet the same pressures might be ineffective against the outside of the shelter. In order to devise protective measures against such hazards, it is desirable to analyze the propagation of these blast pressures and, in particular, to estimate the peak pressure transmitted to an interior chamber.

The anlaysis is based on a plausible generalization of the equations of steady flow through the duct and uses gross parameters of the duct-chamber system which can easily be evaluated. It is therefore applicable to practical situations involving real structures. An exact analysis might conceivably be made by a solution of the exact flow equations for every point on the duct at every instant, but it seems evident that this method would be prohibitively difficult except perhaps for exceedingly simple geometries.

FLOW EQUATIONS

In this analysis the distributed flow resistance in the duct system is divided into two components; a lumped, steady flow resistance, and a lumped inertial resistance. The steady flow resistance, is assumed to be proportional to the mean instantaneous dynamic pressure in the duct, with the proportionality constant depending only on the shape of the

duct system. The justification for this assumption will be discussed in a later section. The inertial resistance is taken as equal to the rate of change of the total momentum of air in the duct.

Thus, if the approach velocity of the air outside the duct is negligible and if

- p_1 is the pressure in the external blast wave,
- p_2, the pressure in the terminal chamber,
- ρ, the average air density in the duct,
- v, the average air velocity along the duct,
- l, the length of the duct,
- A, the cross-sectional area of the duct where velocity is v,
- $q = \rho A v$, the mass flow rate in the duct,
- c, the "loss coefficient" for the duct, and
- V, the volume of the terminal chamber,

then

$$p_1 - p_2 = \frac{c}{2}\rho v|v| + \frac{d(\rho l v)}{dt}$$

$$= \frac{cq|q|}{2\rho A^2} + \frac{l}{A}\frac{dq}{dt} \qquad [1]$$

The mean density in the duct is assumed to be equal to the average of the densities at the two ends, i.e.,

$$2\rho = \rho_1 + \rho_2 \qquad [2]$$

The pressure at the entrance to the duct is assumed to vary with time in the same way as a standard free-field blast wave, and the density is assumed to decay isentropically from its initial shock wave peak.

thus

$$p_1 = p_0 + (p_{10} - p_0)\ e^{-t/\theta}\ (1-\frac{t}{\theta}) \qquad [3]$$

$$\frac{\rho}{\rho_0} = \frac{6\ p_{10} + p_0}{p_{10} + 6\ p_0}\left(\frac{p_1}{p_{10}}\right)^{5/7} \qquad [4]$$

where p_{10} and θ are the peak pressure and the duration of the incident blast wave and p_0 and ρ_0 are atmospheric pressure and density. The total mass of air in the terminal chamber must increase at the rate of the mass inflow into the chamber.

$$\frac{d}{dt}\left(\rho_2 V\right) = q \qquad [5]$$

The mean pressure in the terminal chamber is assumed to rise isentropically. This assumption is a matter of computation convenience and neglects any effects due to the delay in bringing the inflow to rest and the dissipation processes. Hence

$$\frac{p_2}{p_1} = \left(\frac{\rho_2}{\rho_1}\right)^{7/5} \qquad [6]$$

Equations [1] through [6] are sufficient to specify completely the time variation of the pressure and density in the terminal chamber as a function of six parameters, namely, the peak pressure and duration of the blast wave, the shape, length and volume of the duct and the volume of the terminal chamber. However, by a proper choice of nondimensional units, the six parameters can be combined into three nondimensional parameters which completely specify the problem in a more economical way, Thus, if a new set of units for pressure, density, and time is defined by

$$y = \frac{p}{p_0} \qquad z = \frac{\rho}{\rho_0} \qquad x = \frac{t}{\theta} \tag{7}$$

the equations reduce to

$$k^2 \frac{d^2 z_2}{dx^2} + \frac{1}{z_1 + z_2} \left(\frac{dz_2}{dx}\right) \left| \frac{dz_2}{dx} \right| = \frac{y_0 - y_2}{(\gamma\tau)^2} \tag{8}$$

$$y_1 = 1 + \left(y_{10} - 1\right) e^{-x} \left(1-x\right) \tag{9}$$

$$z_1 = \frac{6\, y_{10} + 1}{y_{10} + 6} \left(\frac{y_1}{y_{10}}\right)^{5/7} \tag{10}$$

$$y_2 = z_2^{\ 7/5} \tag{11}$$

where, there remain only three nondimensional parameters y_{10}, τ, and k. The quantity y_{10} is the peak pressure in the external blast wave, measured in units of atmospheres. The parameter τ is defined by

$$\tau = \frac{c^{1/2}\, V}{\gamma \;A\; \theta} \sqrt{\frac{\rho_0}{p_0}} \tag{12}$$

and may be interpreted as a nondimensional "fill time" (fill time in units of the duration θ) for the duct-chamber system. Note that τ depends only on the steady flow characteristics of the duct and is independent of the duct length.

The adiabatic constant γ in Equation [8] could have been incorporated into the definition of τ, but it was desired to retain the same definition as previously used.[1] The remaining parameter k is a measure of the relative importance of the terms for unsteady flow resistance and for steady flow resistance and is defined by

$$k = \sqrt{\frac{\gamma l A}{cV}} \qquad [13]$$

where A here is the mean sectional area along the duct. Thus k^2 is directly proportional to the ratio of duct volume to chamber volume and is inversely proportional to the loss coefficient in the duct.

Equations [8] through [11] are a set of nonlinear equations which must be solved numerically for each set of parameters. This can easily be done with a high-speed computer, and calculated values of the peak chamber pressure have been compiled for a wide range of values of the parameters. In fact, a program is available for the solution of the problem on the IBM 7090 computer for any set of values of y_{10}, τ, and k.

Typical solutions for the pressure in the terminal chamber as a function of time are shown in Figure 1. These curves were calculated for the special case of $y_{10} = 2$ (peak blast overpressure = 1 atm), $\tau = 0.5$, and for three different values of k; k = 0, 0.12, and 0.20. When the unsteady flow resistance is negligible (k = 0), the flow into the terminal chamber continues until the chamber pressure is equal to the external pressure.

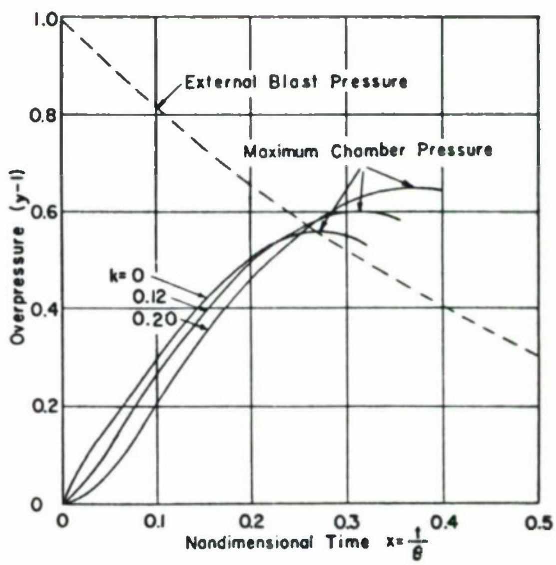

Figure 1 - Variation of Chamber Pressure with Time for $y_{10} = 2.0$, $\tau = 0.5$, and k = 0, 0.12, and 0.20

[1] References are listed on page 14.

At that time the chamber pressure is a maximum, and the flow reverses. The smaller the fill time of the system, the sooner the terminal pressure reaches its maximum, and the closer this maximum pressure is to the peak blast pressure. When the unsteady flow resistance is significant ($k>0$), the chamber pressure rises at a slower rate and continues to rise after the time when it is equal to the external blast pressure because of the inertia of the air in the duct. The chamber pressure may finally reach a peak value that is not very different than that with $k = 0$. If the characteristic fill time τ is small enough and k is large enough, the peak chamber pressure can exceed the peak blast pressure.

The manner in which the peak chamber pressure varies with the three characteristic parameters is shown in Figures 2 and 3, which have been compiled from the numerical solutions. In many practical situations, the inertial ratio k has only a small effect on the peak chamber pressure, and it is particulary significant to consider first how the peak over-pressure in the chamber varies with τ and with y_{10} for $k = 0$.

The variation of the peak overpressure in the chamber is shown in Figure 2. The quantity plotted is the maximum value of $(y_2 - 1) / (y_{10} - 1)$

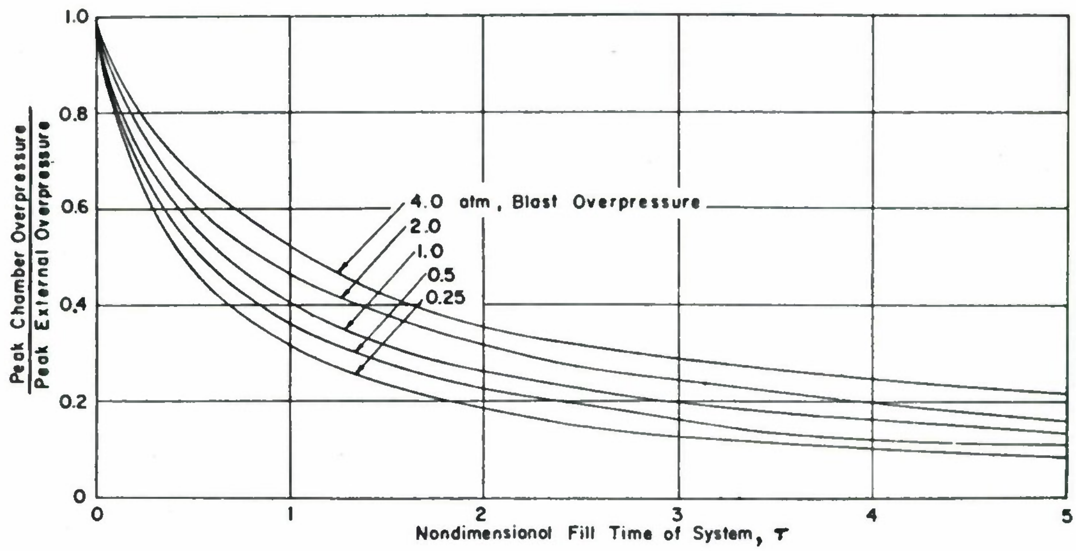

Figure 2 - Dependence of Maximum Overpressure in Chamber on Fill Time of System for $k = 0$ and Blast Pressures of 0.25, 0.50, 1.0, 2.0, and 4.0 Atmospheres

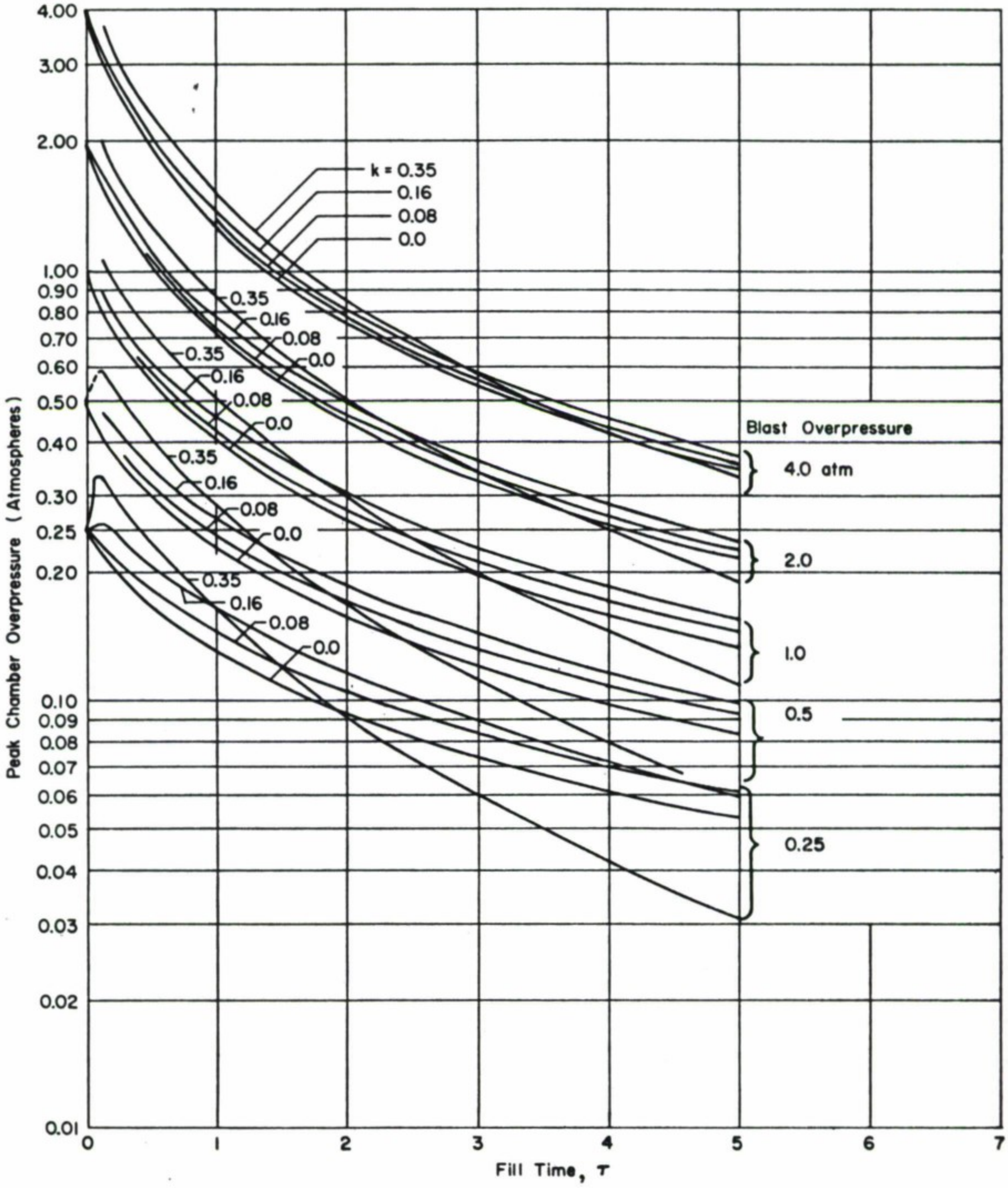

Figure 3 - Variation of Maximum Overpressure in Chamber with k, τ, and y_{10}

which is the ratio of the peak overpressure in the chamber to the peak overpressure in the blast wave. This method of plotting reduces the dependence of the results on the magnitude of the peak blast pressure and makes it easy to interpolate the data for values of the blast pressure other than the five values calculated. The calculations cover the range from $\tau = 0$ to 5.0, and for a peak blast overpressure up to 4 atm (60 psi).

The effects of all parameters on the peak chamber pressure are shown in Figure 3, which is a plot of the peak overpressure in the terminal chamber against the nondimensional fill time τ, with peak blast pressure and inertial constant as variable parameters. It is clear from the curves that, as k increases from 0 to about 0.2, the peak chamber pressure also increases. However, for higher values of the inertial ratio, the net effect of k can be to decrease the peak chamber pressure. Because of the nonlinearity of the flow equations, the peak overpressure in the terminal chamber is not simply proportional to the peak blast pressure. The lower the peak blast pressure, the higher is the ratio of peak chamber overpressure to peak blast overpressure, and the more this ratio is affected by the unsteady flow term.

STEADY FLOW RESISTANCE

The numerical calculations show that the most important parameter in determining the peak chamber pressure is the steady-flow-resistance term, and it is important to justify the form of this term in the equations. For this purpose, consider a steady flow between two ends of a complex duct, where the area at the ends is large enough so that the dynamic pressure can be neglected in comparison with the dynamic pressure in the duct. The flow equation becomes

$$p_1 - p_2 = \frac{c\, q^2}{2\, \rho\, A^2} \qquad [14]$$

This simple equation is in good accord with experimental observations as reported in the technical literature[2,3,4] for steady flow through an arbitrary size and shape of duct provided the pressure difference is small compared with the pressure at either end.

The constant C is termed the loss coefficient for the duct shape and has been measured for a very wide range of duct shapes and tabulated in the technical literature. Note that C ordinarily represents the loss in total or stagnation pressure, measured in units of the dynamic pressure between the two points of a duct. In most cases this loss is not due to a frictional resistance but to an inertial resistance to lateral flow at changes in area or at bends in the duct.

There is also experimental evidence that the loss coefficient remains constant for steady flow even with large pressure differences. For large pressure differences, the density cannot be assumed as constant. Instead we consider that the flow is adiabatic (neglecting friction) and steady, whence the kinetic enthalpy of the air must be constant along the duct, or

$$\frac{p_1}{\rho_1} = \frac{p_2}{\rho_2} \qquad [15]$$

and, if $2\rho = \rho_1 + \rho_2$, the flow equation becomes

$$q = \left[\frac{A^2}{c}\left(\rho_1 + \rho_2\right)\left(p_1 - p_2\right)\right]^{1/2} = \frac{A}{\sqrt{RcT}}\left(p_1^{\,2} - p_2^{\,2}\right)^{1/2} \qquad [16]$$

where T is the temperature and R is the gas constant.

This equation may be compared with the experimental data for the steady flow of air through a thin-edged orifice. The experimental equation of Reference 5 for subcritical flow is identical with Equation [16] if c is taken as 2.70. The experimental equation for supercritical flow is within 3 percent of Equation [16] in the range of pressure ratios up to $p_2/p_1 = 0.1$. This range extends well into the region of supersonic flow. Since an equation of this form is valid for steady flow through a thin-edged orifice, it seems plausible that it should also be valid for steady flow, even with large pressure differences, through any duct shape, because the arbitrary duct can be considered as a series arrangement of thin-edged orifices.

It is convenient to define the combination $\alpha = A/\sqrt{c}$ as the "effective area" of the duct. It depends on both the shape and size of the duct segment and, incidentally, on the direction of flow. The effective area of a complex duct system can be calculated from the loss coefficients, or effective areas, of its parts. Thus, for several duct sections in series, where the flow rate is the same in all sections, the effective area of the combination is given by

$$\frac{1}{\alpha^2} = \sum_i \frac{1}{\alpha_i^2} \qquad [17]$$

While for several sections in parallel, where the terminal pressures are common to all sections, the effective area of the combination is

$$\alpha = \sum_i \alpha_i \qquad [18]$$

It is precisely because the loss coefficients, or effective areas, can be estimated so easily, or determined experimentally if necessary, that an attempt was made to formulate the transient flow equations in terms of these loss coefficients.

An illustration of the practical calculation of the effective area and its use in predicting the peak chamber pressures are given in the Appendix. As a rough guide, it can be expected that the effective area of a duct is equal to half of the area of the smallest section.

RANGE OF APPLICATION

Since the analysis is not based on the basic flow equations for a gas, the range in which the analysis is valid must be determined by a careful comparison of experimental results with calculated values. A review of some of the assumptions shows where deviations can be expected.

First, the numerical results are valid only if the external blast pressure varies in the ideal way prescribed by Equations [3] and [4]. This variation is obviously a poor approximation in many cases of practical interest. For example, the blast pressures can be greatly

changed by the presence of nearby reflecting surfaces or diffracting bodies. In that case, it would be necessary to modify Equations [3] and [4] accordingly, but the resulting equations could still be solved numerically if the proper modifications were specified. Equation [1] also assumes that the incident blast wave has no appreciable velocity component into the duct. Otherwise it would be necessary to replace p_1 in Equation [1] by $p_1 + \rho v_1{}^2/2$ where v_1 is the approach velocity.

There are also some obvious approximations in the boundary conditions for the terminal chamber. The isentropic assumption neglects heat flow to the walls and irreversible processes in the duct, but this is estimated to have a minor effect on the peak chamber pressure so long as the peak is less than, say, 2 atm. It is also assumed that the flow into the chamber is in immediate equilibrium with the air in the chamber. In reality, large currents and large pressure gradients may exist in the terminal chamber, and the peak pressure which is computed would only be a fair estimate if the relaxation time of these currents were small compared with the fill time of the chamber.

The major approximation is probably due to the lumpimg assumption. This assumption immediately implies that we cannot deduce the pressure distribution in the duct itself. The flow in the duct could be unstable for certain terminal conditions whereas the analysis tacitly assumes stability. The flow pattern in the duct, the appearance and location of shock fronts, etc., will all depend on the instantaneous terminal conditions and whether the local flow is subsonic or supersonic, but the use of a single lumped effective area and single lumped longitudinal inertia term obviously disregards these complexities. One justification for this is that, in practical cases, the major contribution to the effective area is due to the entrance geometry of the duct and to the exit geometry, and both of these are analogous to thin-edged orifices for which the effective area is valid experimentally.[3] The lumped inertia term is difficult to evaluate because it is uncertain how much of the total air in the duct participates in the average flow. Fortunately, so long as the duct is small compared with the chamber volume, the peak chamber pressure is rather insensitive to the precise value of the inertia term.

APPENDIX - SAMPLE CALCULATION

As an illustration in the use of this analysis, we consider the duct-chamber system shown in Figure 4 and calculate the peak pressure transmitted to the terminal chamber when an ideal blast wave with a peak overpressure of 20 psi and a duration of 0.8 sec passes over the entrance to the duct.

We first compute the effective area of the duct. Consider the four sections, labeled (1) to (4) in Figure 4, at which there is a change in area or direction, and tabulate the loss coefficient and section area for each. The loss coefficient is determined from Tables 2 and 3 of Reference 2. We next include the effective loss coefficients due to friction and assume that it is sufficiently accurate to take these as

$$C_f = \frac{1}{39} \frac{\text{length of duct}}{\text{diameter of duct}} \qquad [19]$$

as is customarily done for steady flow at low velocities.

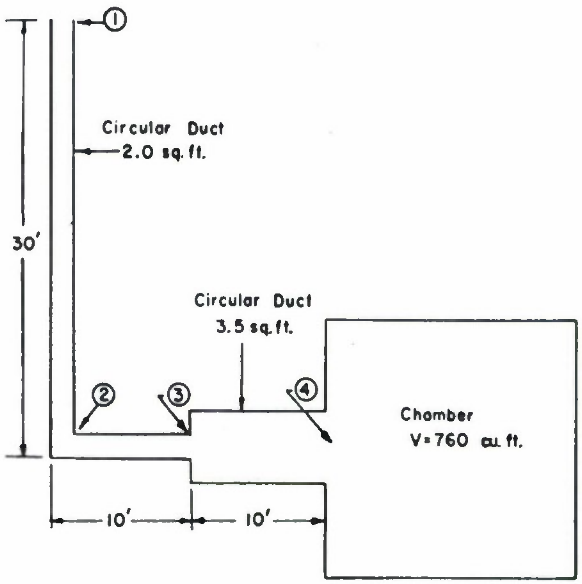

Figure 4 - Duct-Chamber System

TABLE 1

Computed Values for Duct-Chamber System of Figure 4

Section	Area A sq ft	Loss Coefficient c	$\frac{c}{A^2}$
Entrance (1)	2.0	0.85	0.212
Bend (2)	2.0	1.30	0.322
Expansion (3)	3.5	0.50	0.041
Exit (4)	3.5	1.00	0.082
Friction in small duct	2.0	0.64	0.160
Friction in large duct	3.5	0.12	0.010

For the entire duct

$$\frac{1}{\alpha^2} = \sum \frac{c_i}{A_i^2} = 0.827$$

and the equivalent area $\alpha = 1.10$ sq ft which is 55 percent of the area of the smallest section. The system fill time, in nondimensional units, is

$$\tau = \frac{0.845V}{\alpha\, a\, \theta} = 0.58$$

where a is the initial sound speed in the duct.

The inertial ratio is

$$k = \sqrt{\frac{\gamma l A}{cV}} = 0.22$$

Now from Figure 3 when the peak blast overpressure is 1 atm, $\tau = 0.58$, and $k = 0.22$, the peak overpressure in the chamber is about 61 percent of the peak blast overpressure. While for a peak blast overpressure of 2 atm, $\tau = 0.58$, and $k = 0.22$, the peak overpressure in the chamber is about 54 percent of the peak blast overpressure. Hence, for a peak blast overpressure of 20 psi (1.34 atm), the peak chamber overpressure would be about 59 percent of the peak blast overpressure, or 12 psig.

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